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The following is a translation of an article entitled "Silicon Solar Batteries as Electric Power Sources for Artificial Earth Satellites" from the magazine Uspekhi Fiziki Nauk, Vol. 63, No. 1, September 1957, by V. S. Vavilov, V. M. Malovetskaya, G. N. Galkin and A. P. Landsman.

The supply of energy to scientific apparatus and telemetering apparatus on earth satellites from accumulators or storage batteries and from primary cells aboard the satellite can only last for a short period of time. Prolonged use of the scientific apparatus can only be achieved through the use of solar energy. Of the existing methods of utilization of solar energy into electrical energy, the most promising seems to be the photoelectric semiconducting converters. (The use of semiconductor thermocouples, having approximately the same efficiency, but being of much greater weight, probably will become reasonable when the total size and weight of the satellite reaches greater dimensions.)

Solar batteries in connection with accumulators is a reasonable combination for use on oriented artificial satellites, because in such a case maximum effectiveness of the satellite can be assured for the duration of its life.

#### 1. The Principle of Operation of the P-N Junction Converter.

The first step in the conversion of solar energy into electrical energy is the absorption near the P-N junction of a photon which forms a hole electron pair. In the absence of the P-N junction there would merely occur an increase in the concentration of electrons and holes in the semiconductor, this constituting an increase in conductivity and the resulting phenomenon being referred to as photoconductivity.

Let us study the diagram of electron energy conditions and hole energy conditions in the semiconductor near the artificially constructed P-N junction to explain the principle of solar energy conversion by the photoelectric cell. (Here reference is made to a standard band gap diagram for a semiconductor such as can be found at page 78 of the book An Introduction to Semiconductors by W. Crawford Dunlap, Jr., published by John Wiley & Sons.) In the drawing there are shown the conduction band and the valence band separated by the forbidden band or energy gap. From the diagram it is obvious that in the region of the P-N junction there exists a potential barrier, the magnitude of which ( $V_k$ ) can be close to the width of the forbidden band or energy gap  $E_g$ , which for silicon is 1.1 electron volts.

The electrons and holes produced upon the absorption of light diffuse towards the P-N junction. We may assume that the potential barrier at the P-N junction separates the holes and electrons because electrons pass freely into the region of electronic conductance (N-portion) of the crystal, charging it negatively, but the holes, passing into the region of hole conductivity (P-region) charge it positively. As a result of the change in the concentration of the charge carrying particles, the magnitude of the potential barrier decreases. If the circuit is opened, there occurs a dynamic equilibrium of the primary diffusing current  $I_d$  of surplus carriers (for example, the holes from the N-region of the crystal moving to the P-region) and the current, moving in the reverse direction (caused by this spacial charge of surplus holes in the P-region and electrons in the N-region). If the circuit is closed, the diffusing current will travel through it. In an intermediate case, corresponding to actual oper-

ating conditions as a converter coupled to a load, there is a branching off effect in the currents, one for the load circuit and another for the internal stabilization of the crystal potentials. The sum of these currents is equal to the diffusing current which in a general case can be shown to be:

$$(1) \quad I_d = \int_{\gamma_{\min}}^{\gamma_{\max}} N_h \gamma (1 - R(\gamma)) q \alpha(\gamma) d\gamma$$

$$\gamma_{\min} = \frac{E_g}{h}$$

where  $N_h \gamma$  is the number of photons falling on the surface of the semiconductor in one second with an energy  $h\gamma > E_g$ . Strictly speaking, equation (1) can only be used in the region where the quantum output equals 1. In practice, this is true for silicon up to  $h\gamma = 3$  ev. In the further removed portions of the ultra-violet spectrum there is a possibility of further increase of the carriers on account of impact ionization with the photoelectrons or holes. But the percentage of energy of the solar spectrum reaching the converter in this region is small, and one may assume that  $h\gamma_{\max} = 10$  ev. is a very good approximation. Usually, the value of  $\alpha$  decreases sharply on account of surface recombinations for short wave-lengths. One may assume that the whole number of carriers generated by solar radiation in the silicon is, in the absence of reflection, and  $\alpha = \text{const.} = 1$ , equal to the current  $I_d = 0.035$  amperes per square centimeter at sea level and will increase approximately to 0.040 amperes per square centimeter outside the Earth's atmosphere.

The term "R" in the foregoing equation is the coefficient of reflection which is a function of the frequency of the incident illumination. The term "q" is the charge on an electron and  $\alpha$  is a coefficient, less than 1, which can be called the effective quantum output. The electromotive force, generated by the semiconducting converter, and its efficiency depend very much upon the magnitude of the saturation current  $I_s$  of the P-N junction but can be defined mainly by the width of the forbidden energy gap of the semiconductor. In the case of not too great an excess of carrier concentration, the electromotive force or voltage of the converter equals:

$$(2) \quad V = \frac{KT}{q} \ln \left( \frac{I_d R_0}{KT} + 1 \right)$$

where  $R_0$  is the resistance of the P-N junction at zero field intensity, equaling

$$\frac{KT}{qI_s}$$

It has been shown that this formula corresponds very well to the empirical results attained with germanium photocells. It has been approximated that this formula also holds in the case of direct solar light falling upon silicon photocells. In the work done by Prince, who investigated the question of maximum efficiency of solar batteries, there exists a curve relationship of maximum efficiency related to the width of the forbidden energy gap. (Here is shown a Figure 2 which relates efficiency to energy gap. I believe this is work done by Mort Prince while he was still at Bell.)

Disregarding some arbitrary assumptions about the magnitude of the meaning of some of the other numerical values which have an effect on the efficiency (for example, the relationship of the diffusion lengths and conductances and the assumption of the absence of reflection) the curve of Figure 2 gives a visual idea of the possibilities of using solar batteries, both those already tried and those that may be developed. There exists no doubt that at the present time the best semiconductor solar energy converter is silicon.

We should point out the fact that in not a single case known to the authors has the theoretical efficiency of 22% been attained. In the last several years much information has been published about experimentation with silicon, germanium, and other photocells for the purpose of transforming solar energy. The efficiencies reached in experimental constructions has been from 6% to 7%; in one experiment with separate silicon elements, an efficiency of 11% was reached which is the equivalent at sea level and with full noonday illumination of about 100 watts on a square meter of useful converter surface.

The authors have developed a method for effecting P-N transformations in mono-crystal silicon of the P-type by using thermal diffusion of phosphorus from the gaseous phase. This method makes it possible to obtain junctions at a precisely specified depth from the surface of the crystal which is important in silicon photocells in which there is a short length of carrier diffusion with unequal carrier equilibriums. Soon more information will be published.

To obtain sufficiently large coefficients of conversion  $\alpha$ , the depth of location of the P-N junction has to be less than the length of diffusion of the holes in the N-silicon layer which has been diffused with phosphorus. During the experiment it was discovered that the lifetime of the charge carriers in the silicon decreases noticeably during the heat treatment necessary for the diffusion of phosphorus into the silicon. This has already been pointed out by Fuller. Disregarding this obstacle, measurement of the coefficients of accumulation or conversion  $\alpha$  point to the fact that excess carriers formed by the converted photons of wave lengths from 1.1 to 0.4 microns, are absorbed at sufficiently small depths of the P-N junction to an average of about 50%. Based on the foregoing data, one can assert that the value of  $\alpha$  depends to a great extent on the speed of surface recombinations.

A further decrease in the thickness of the N-layer on the surface of the silicon by the method of sandblasting or etching leads to a significant increase in the coefficient of conversion. But an excess decrease in the thickness of the N-layer, which has a significantly great useful surface area causes a decrease in efficiency on account of the increasing IR drop in the layer when an external load is connected to the converter. The matter of the significance of series resistance has been studied in experiments that have all been germanium photocells and also by Prince. A decrease in the magnitude of the series resistance to a minimum has a definite significance. The resistance of the converting layer can be reduced by the application of a semi-transparent electrode. But this method results in a decrease in efficiency because of the absorption of light by the metal. That loss of efficiency surpassing the increase in efficiency effected by reduction of the series resistance. Another possibility is the application of a metallic grid of

great transparency. Also, beside the above considerations, it is necessary to lower the resistance at the ohmic contact.

(There follows a figure showing the spectral response of a silicon solar energy converter with two differing diffusion depths. The first being about 15 microns and the second about 9 microns. The greater depth of diffusion results in a maximum response at a longer wave length. (BLB) (Figure 4 shows a cross-section of a solar cell made according to the writers' concept. This cell substantially conforms to the configuration of our old S-1 cell in that the positive and negative contacts are both on the back side of the cell. Of course, here the base material is P-silicon and an N-layer is diffused into the surface utilizing phosphorus in the gaseous phase. (BLB)

As can be seen from Figure 4 the entire upper surface of the silicon is useful for conversion of light energy into electrical energy. The surface area of a single photocell is only dependent upon the initial dimensions of the mono-crystal and can be at this time from 5 to 8 cm<sup>2</sup>. The thickness of the plate usually is about 0.7 to 1.0 mm.

## 2. The Volt-Ampere and Loading Characteristics.

The volt-ampere characteristic of a photocell upon which solar energy is impinging is given in Figure 5 (surface area of cell equals .95 cm<sup>2</sup>). (Comments: This curve shows a characteristic substantially that of our old S-1 cell and shows, in addition, a curve for a silicon converter having zero internal series resistance. This curve looks substantially like that of our 2A or our 120C cells. BLB)

The volt-ampere characteristics of the cell may be described by the formula:

$$(3) \quad I = I_s \left( \frac{q}{e A K T} (V - I R_{succ.}) - 1 \right)$$

where A = 1.4. Comparing the theoretical volt-ampere characteristics of the P-N junction and the theoretical characteristics of the photocell one can compute the total series resistance and determine the maximum efficiency for the converter.

The optimum agreed upon resistance of the load can be determined empirically or by way of calculations.

Using a photocell of an area approximating .95 square centimeters, with the cell exposed to normal solar incidence, the optimum value of load resistance was found to be equal to 39 ohms. With the photocell placed beneath a layer of water 4 cm thick and exposed to a lamp of 500 watt rating, the short circuit current in the cell reached 125 milliamperes per square centimeter with a voltage generated of more than .65 volts. This fact permits the observation that with the proper attention paid to heat sinking one can significantly decrease the necessary area of the solar battery by use of solar energy concentrators.

Without showing detailed calculations, there follow four other possibilities for increasing the efficiency of conversion of the solar cells:

| <u>Method of increasing efficiency</u>   | <u>Probable increase in efficiency</u>          |
|--|---|
| 1. Increasing coefficient of use $\mathcal{L}$ to 1  | About double                                    |
| 2. Decreasing of successive $R_{succ} \ll R$   | About 1.5 times                                 |
| 3. Light upon surface when $R = 0$   | About 1.35 to 1.4 times                         |
| 4. Improvement of form of load characteristic by way of utilizing a material of minimum resistivity (without changing meaning of $\mathcal{L}$ ) | Not certain yet. Further experiments necessary. |

If at the same time there is an increase of  $\mathcal{L}$  until it approaches a value of 1 and there is a decrease in the series resistance, an efficiency of 15% can be attained; analysis indicates difficulty and improbability in improving the loading characteristic of the converter, as can be seen by referring to the curve of Figure 5 in which a series resistance of zero is considered.

### 3. Temperature Effects on the Solar Battery.

In agreement with the theory, the voltage produced by a silicon photocell increases with a decrease of temperature. Previous examination of a change in voltage with temperature gave the following relationship:

$$(4) \quad \frac{dV}{dT} = -0.00252 \text{ V/}^{\circ}\text{C.}$$

Note: Prince gave the relationship as  $\frac{dV}{dT} = -0.00288 \text{ V/}^{\circ}\text{C.}$

In Figure 6 we show the dependence of V upon temperature in the region of  $-70^{\circ}$  to  $+90^{\circ}\text{C.}$

It is obvious that for maximum output from a solar battery in flight, a low equilibrium temperature of the solar battery should be attained. An approximate calculation of the thermodynamic system for a silicon photocell is quite simple. The coefficient of reflection of silicon in the region of the solar spectrum is the main consideration and has been well studied and is well known. It can be taken as equal to 0.35. In the region of major radiation at low temperatures (close to  $300^{\circ}\text{K.}$ ) the silicon appears to be a non-selective "grey body" with a coefficient of radiation equal to 0.7. Assuming the solar constant to be equal to 0.135 watts per square centimeter, from the equation of heat equilibrium and the law of Stephan, one can determine with an error not greater than 5% the absolute temperature of the silicon sheet upon which the solar rays are falling normally. This temperature is equal to  $324^{\circ}\text{K.}$  (lucidity of silicon with wave length greater than 1.1 microns has not been considered). This temperature appears reasonably correct; but the efficiency can be significantly increased by making the rear surface of the solar battery "black" in the region of 2 to 15 microns and by increasing the surface

area of heat dissipation. An approximation shows that with this approach it is possible to reach a temperature equilibrium not higher than 260° to 270°K. A further decrease of working temperature and at the same time an increased efficiency in the utilization of the active part of the solar spectral radiation can be accomplished by applying an interference layer on the surface for the region of 0.5 to 0.9 microns with a simultaneous increase in the coefficient of reflection immediately beneath the surface region. Obviously, before a practical application of this method can be attained, much experimentation must be done on earth under simulated conditions.

Experience in using solar batteries under earth conditions has given completely identical positive results. Under conditions of the lengthy flight of a satellite, this method for gaining energy appears to be the only feasible one which makes the necessary hard work in achieving the desired results very worthwhile.

Developing data about the actual thermal conditions, the efficiency, the flow of energy of solar radiation and the actual testing of solar batteries will permit the construction of solar batteries of significant area, built for lengthy periods of use on a satellite.

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